

Meson Production and Meson Properties at Finite Nuclear Density*

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The properties of π, η, K^+ and K^- mesons are studied in nuclear reactions from SIS to SPS energies within the covariant transport approach HSD in comparison to the experimental data. Whereas the pion, η and kaon abundancies and spectra indicate little or vanishing self-energies for these mesons in the medium, antikaons (as well as antiprotons) are found to experience strong attractive potentials in nucleus-nucleus collisions at SIS energies. However, even when including these potentials the K^+ and K^- spectra at AGS energies are noticeably underestimated showing an experimental excess of strangeness that points towards a nonhadronic phase in these reactions. On the other hand the K^+, K^- production at SPS energies is well described by the hadronic approach without incorporating any parton degrees of freedom.

1. Introduction

The aim of high energy heavy-ion collisions at the GSI Schwerionen Synchrotron (SIS), the Brookhaven Alternating Gradient Synchrotron (AGS) and the CERN Super Proton Synchrotron (SPS) is to investigate nuclear matter under extreme conditions, i.e. high temperature and density. The most exciting prospect is the possible observation of a signal for a phase transition from normal nuclear matter to a nonhadronic phase, where partons are the basic degrees of freedom. In this context strangeness enhancement in heavy-ion collisions compared to proton-proton collisions has been suggested as a possible signature for the phase transition [1]. On the other hand, precursor effects might already be seen at SIS energies since densities up to $3 \times \rho_0$ can be achieved in central collisions of heavy nuclei [2] and the effect of meson potentials can be studied with a higher sensitivity to the

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productions thresholds, respectively. Furthermore, dilepton spectroscopy should be well suited to investigate the in-medium properties of especially the ρ -meson which due to its short life time preferentially decays in the medium [3].

In this contribution a brief survey is presented on the information gained so far in comparison of experimental data to nonequilibrium transport theory, here the Hadron-String-Dynamics (HSD) approach [4]. For a more detailed discussion of the issues presented the reader is referred to a recent review [3].

2. Analysis of meson properties from SIS to SPS energies

The production of particles especially at 'subthreshold' energies is expected to provide valuable information about the properties of hadrons at high baryon density and temperature [2]. Their relative abundance and spectra should reflect the in-medium properties of the particles produced since for a 'dropping' mass – i.e. a reduced quasiparticle energy in the medium,

$$m^* = \omega(\mathbf{p} = 0) = \sqrt{m_0^2 + \Pi_h(\rho_B, \rho_S, \mathbf{p} = 0)}, \quad (1)$$

where $\Pi_h(\rho_B, \rho_S, ..)$ denotes the meson self-energy as a function of the baryon density ρ_B and scalar density ρ_S – the particle can be created more abundantly. On the other hand it will be suppressed in case of repulsive potentials. Furthermore, a quasiparticle feeling an attractive potential at finite baryon density will be decelerated during its propagation out of the medium and thus asymptotically its momentum spectrum will be enhanced at low relative momenta with respect to the baryon matter rest frame [5]. The opposite holds in case of repulsive potentials.

As mentioned above the dynamics of hadron-hadron, hadron-nucleus and nucleus-nucleus collisions is described within the HSD transport approach [4] that so far has been well tested in a large dynamical domain [6]. We start with pion and η dynamics at SIS energies. The transverse-mass spectra of π^0 and η mesons in heavy-ion collisions up to 2 A·GeV have been measured by the TAPS Collaboration [7, 8, 9] and a m_T scaling has been observed for both mesons. The same scaling can be found in the HSD transport calculations when including no pion and η -meson self-energies. In Fig. 1 we compare the results of the calculation [10] for the inclusive transverse-mass spectra of π^0 and η mesons with the TAPS data. The r.h.s. shows the m_T spectra for π^0 's (dashed histogram) and η 's (solid histogram) for C + C at 1.0 A·GeV in the rapidity interval $0.42 \leq y \leq 0.74$ and at 2.0 A·GeV for $0.8 \leq y \leq 1.08$. The experimental data – the open circles and solid squares

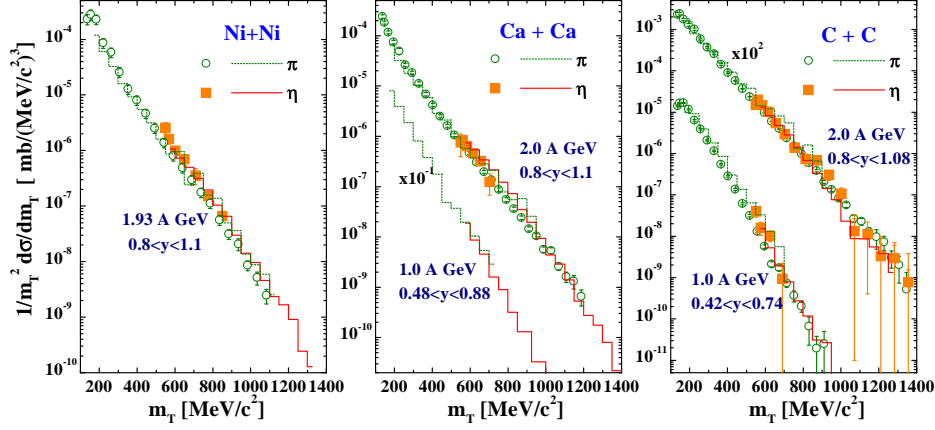


Fig. 1. The calculated transverse mass spectra for neutral pions and η -mesons in comparison to the data from the TAPS Collaboration (see text).

correspond to π^0 and η mesons, respectively – are taken from Ref. [8]. The theoretical results as well as the experimental data at 2.0 A-GeV here are multiplied by a factor of 10^2 . The middle part corresponds to Ca + Ca at 1.0 A-GeV for $0.48 \leq y \leq 0.88$ (multiplied by 10^{-1}) and at 2.0 A-GeV for $0.8 \leq y \leq 1.1$ in comparison with the data from Ref. [9]. The l.h.s. shows the calculated m_T spectra for Ni + Ni at 1.93 A-GeV for $0.8 \leq y \leq 1.1$ in comparison with the data from Ref. [9]. As seen from Fig. 1 the HSD transport model gives a reasonable description of the m_T spectra of pions and η 's as measured by the TAPS Collaboration without incorporating any medium modifications for both mesons. It is important to point out that these calculations are parameter-free in the sense that all production cross sections for η mesons are extracted from experimental data in the vacuum and the η -nucleon elastic and inelastic cross sections are obtained by using detailed balance on the basis of an intermediate N(1535) resonance. As shown in Ref. [10] an attractive potential for the η -meson would lead to a violation of the m_T scaling found experimentally. Without explicit representation we note that the pion and η spectra at AGS and SPS energies also do not indicate sizeable in-medium effects [3].

Kaons and antikaons have shown to be more promising in this respect [11, 12]. Since the real part of the actual K^+ and K^- self-energy Π_h in (1) is quite a matter of debate we adopt a more practical point of view and as a guide for the analysis use a linear extrapolation of the form,

$$m_K^*(\rho_B) = m_K^0 \left(1 - \alpha \frac{\rho_B}{\rho_0} \right), \quad (2)$$

with $\alpha_{\bar{K}} \approx 0.2$ -0.25 for antikaons and $\alpha_K \approx -0.06$ for kaons. Alternative fits

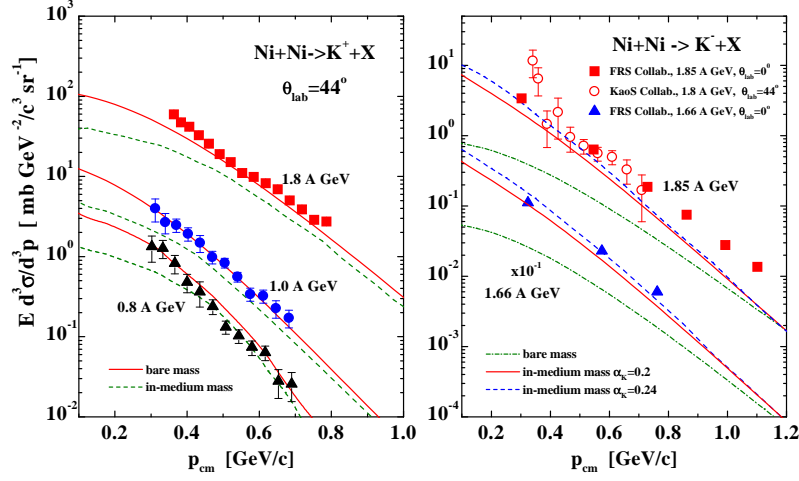


Fig. 2. The calculated K^+ (l.h.s.) and K^- (r.h.s.) momentum spectra in the nucleus-nucleus cms for Ni + Ni reactions for different meson potentials in comparison to the experimental data (see text).

to the antikaon self-energies lead to different values for the parameter $\alpha_{\bar{K}}$ in the range $0.1 \leq \alpha_{\bar{K}} \leq 0.3$ (cf. Ref. [13]). The choice $\alpha_{\bar{K}} \approx 0.2$ leads to a fairly reasonable reproduction of the antikaon mass from Refs. [14, 15, 16] and the results from Waas, Kaiser and Weise [17]. In (2) a momentum dependence of the kaon or antikaon potential has been neglected for reasons of numerical simplicity. The dispersion analysis of Sibirtsev et al. [18] shows that this is roughly fulfilled for the kaon potential, however, the antikaon potential should be more strongly momentum dependent.

The Lorentz invariant K^+ spectra for Ni + Ni at 0.8, 1.0 and 1.8 A·GeV are shown in Fig. 2 (l.h.s.) in comparison to the data from the KaoS Collaboration [19]. Here the full lines reflect calculations including only bare K^+ masses ($\alpha_K = 0$) while the dashed lines correspond to calculations with $\alpha_K = -0.06$ in Eq. (2), which leads to an increase of the kaon mass at ρ_0 by about 30 MeV. The general tendency seen at all bombarding energies is that the calculations with a bare kaon mass seem to provide a better description of the experimental data for Ni + Ni than those with an enhanced kaon mass. This trend continues to hold also for the light system C + C as well as for the heavy systems Ru + Ru and even Au + Au [3]. Furthermore, this tendency is also confirmed by the independent calculations from Li et al. [12].

On the other hand, the kaon flow in the reaction plane should show some sensitivity to the kaon potential in the nuclear medium as put forward by Li, Ko and Brown [20, 21]. Here due to elastic scattering with nucleons the kaons partly flow in the direction of the nucleons thus showing a positive

flow in case of no mean-field potentials [20]. With increasing repulsive kaon potential the positive flow will turn to zero and then become negative. In fact, experimental data on kaon flow indicate a slightly repulsive potential for kaons in the nuclear medium [22]. Further data with cuts on centrality are expected to allow for more definite conclusions [23].

We now turn to the production of antikaons which similar to antiprotons [24] do clearly show the effect from attractive potentials in the medium. We recall that for $\alpha_{\bar{K}} = 0$ in Eq. (2) we recover the limit of vanishing antikaon self-energy, whereas for $\alpha_{\bar{K}} \approx 0.2$ we approximately describe the scenario of Kaplan and Nelson [14, 15] or Waas, Kaiser and Weise [17]. For practical purposes one should consider $\alpha_{\bar{K}}$ to be a free parameter to be fixed in comparison to the experimental data in order to learn about the magnitude of the antikaon self-energy. The K^- spectra for Ni + Ni at 1.85 and 1.66 A·GeV from Refs. [25, 26] are shown in Fig. 2 (r.h.s.) for $\alpha_{\bar{K}} = 0, 0.2$ and 0.24 where the latter cases correspond to an attractive potential of -100 and -120 MeV at density ρ_0 , respectively. We note, that due to the uncertainties involved in the elementary BB production cross sections we cannot determine this value very reliably. With increasing $\alpha_{\bar{K}}$ not only the magnitude of the spectra is increased, but also the slope becomes softer. This is most clearly seen at low antikaon momenta because the net attraction leads to a squeezing of the spectrum to low momenta. As seen from Fig. 2 the K^- spectra at 1.85 A·GeV are underestimated at high antikaon momenta which might indicate the necessity for explicit momentum dependent antikaon potentials [18].

Whereas the kaon and antikaon dynamics at SIS energies is reasonably described within the hadronic transport approach HSD when including meson potentials [3], this no longer holds at AGS energies [3]. The heaviest system studied here is Au + Au at ≈ 11 A·GeV. The calculated π^- , K^+ and K^- rapidity spectra for central (0-10%) reactions ($b \leq 2$ fm) are displayed in Fig. 3 in comparison to the data from Ref. [28]. The solid histograms correspond to the 'bare mass' scenario and underestimate the data strongly whereas the dashed histograms are obtained for $\alpha_K = -0.06$ and $\alpha_{\bar{K}} = 0.24$, respectively. Whereas the K^- yield is almost reproduced in the latter scheme, the K^+ yield is still underestimated as in case of the Si + Au system at 14.6 A·GeV [27].

We now step on to SPS energies. The calculated results for the negative hadron (h^-) (l.h.s.), kaon (middle) and antikaon (r.h.s.) rapidity distributions for central collisions of Pb + Pb at 160 A·GeV are shown in Fig. 4 in comparison to the data from [29]. The solid histograms correspond to the 'bare mass' scenario whereas the dashed histograms reflect the 'in-medium mass' case with $\alpha_K = -0.06$ and $\alpha_{\bar{K}} = 0.24$. As for S + S at 200 A·GeV [27] the h^- , K^+ and K^- distributions are reproduced rather well showing even a

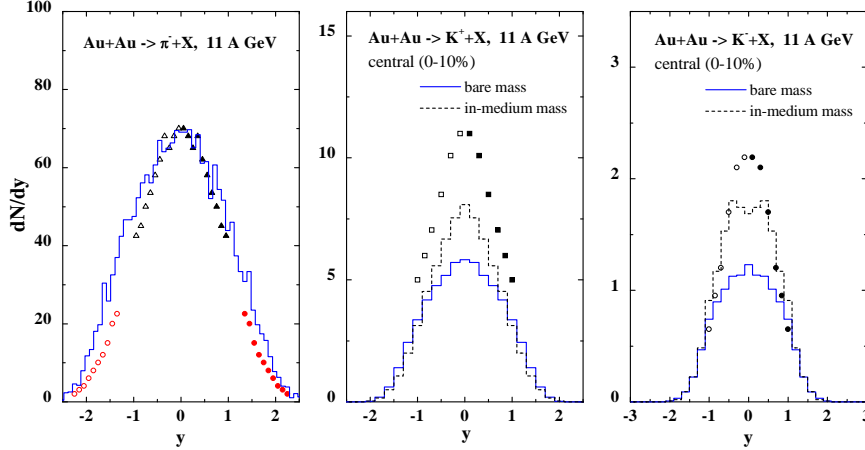


Fig. 3. The calculated π^- (l.h.s.), K^+ (middle) and K^- (r.h.s.) rapidity spectra for central Au + Au reactions at 11 A·GeV in comparison to the experimental data. The solid histograms are obtained without meson potentials whereas the dashed histograms represent calculations with the same potentials as at SIS energies (see text).

tendency for an excess of kaons and antikaons in the calculations rather than missing strangeness. The distribution in rapidity becomes slightly broader for in-medium kaon masses (dashed histograms in Fig. 4), but both scenarios are compatible with the present data. Kaon and antikaon self-energies thus are hard to extract from data at SPS energies due to the low sensitivity of the spectra on in-medium potentials. We mention that the strangeness enhancement at SPS energies in nucleus-nucleus collisions does not qualify as a signal for an intermediate quark-gluon plasma (QGP) phase since the spectra are fully compatible with a hadronic reaction scenario. However, the strangeness production at much lower energy appears more promising [27].

The E866 and E895 Collaborations recently have measured Au + Au collisions at 2,4,6 and 8 A·GeV kinetic energy at the AGS [30]. Thus it is of particular interest to look for a *discontinuity in the excitation functions* for pion and kaon rapidity distributions and to compare them to the hadronic HSD transport approach. In Fig. 5 the calculated K^+/π^+ ratios (open squares) at midrapidity ($|y_{cm}| \leq 0.25$) for central ($b=2$ fm) Au + Au collisions at 1,2,4,6,8 and 11 A·GeV and Pb + Pb collisions at 160 A· are shown together with the preliminary data (full dots). The ratio at midrapidity is slightly higher than the total K^+/π^+ ratio, because the kaon rapidity distribution is narrower than that of the pions. While the scaled kaon yield at 1 and 2 A·GeV (SIS energies) is well described in the HSD approach within

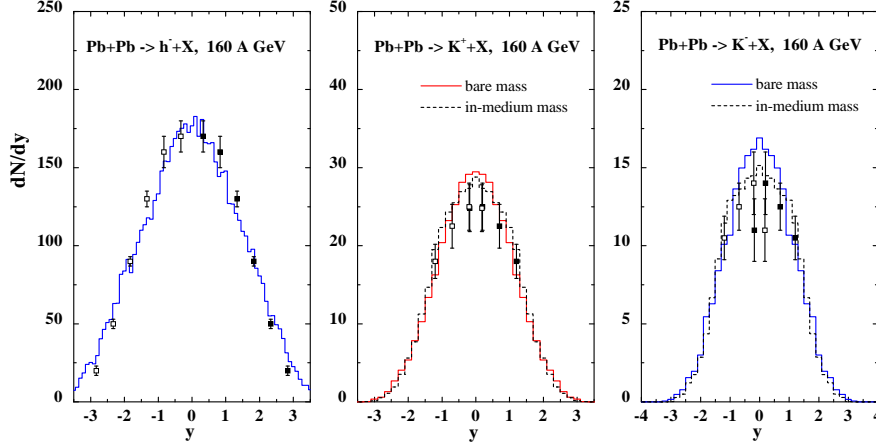


Fig. 4. The calculated h^- (l.h.s.), K^+ (middle) and K^- (r.h.s.) rapidity spectra for central Pb + Pb reactions at 160 A·GeV in comparison to the experimental data. The solid histograms are obtained without meson potentials whereas the dashed histograms represent calculations with the same potentials as at SIS energies (see text).

the errorbars, the experimental K^+/π^+ ratio at 4 A·GeV is underestimated already by a factor of 2 and increases up to roughly 19% for 11 A·GeV. As mentioned before the calculated and measured ratio coincide again at 160 A·GeV.

The increase of the K^+/π^+ ratio with bombarding energy in the HSD approach is much slower up to 11 A·GeV in comparison to the data and similar to the corresponding ratio for p + p collisions (open circles) in HSD. The relative strangeness enhancement in the transport approach for Au + Au compared to p + p is due to Fermi motion and hadronic rescattering; obviously this hadronic rescattering scenario is insufficient to describe the experimental excitation function.

3. Summary

Pions and η -mesons are found not to show sizeable in-medium effects in their relative abundancy and spectra. The same holds for kaons where only the data on kaon flow indicate a slightly repulsive potential. Antikaons similar to antiprotons [3, 24], however, do show strong attractive potentials in the medium which is seen most clearly at 'subthreshold' production energies in nucleus-nucleus collisions. The magnitude of the K^+ , K^- potentials seen at finite density is roughly in line with Lagrangian models based on chiral

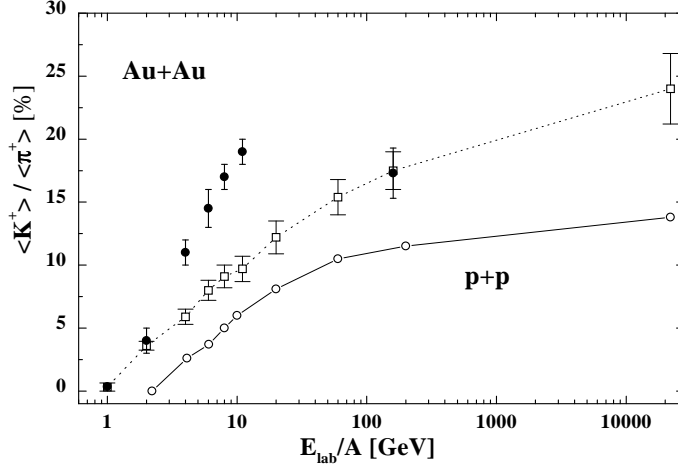


Fig. 5. The calculated K^+/π^+ ratio at midrapidity for central Au + Au reactions (full squares) from SIS to RHIC energies in comparison to the preliminary experimental data from 1 - 160 A-GeV and the corresponding ratio for p + p collisions (open circles) from the HSD approach (see text).

perturbation theory [14, 17] and relativistic mean-field approaches [13].

An enhancement of the K^+/π^+ ratio in heavy-ion collisions relative to p + p reactions is found due to hadronic rescattering both with increasing system size and energy. It should be emphasized that this is expected within any hadronic model: the average kinetic energy and the particle density increases monotonically with incoming kinetic energy of the projectile while the life time of the fireball increases with the system size. The excitation function in the K^+/π^+ ratio from the hadronic transport approach has a similar slope in nucleus-nucleus and p + p collisions (cf. Fig. 5) indicating a monotonic increase of strangeness production with bombarding energy. However, the experimental K^+/π^+ ratio for central Au + Au collisions at midrapidity increases up to $\approx 19\%$ at 11 A-GeV – it is unknown if a local maximum will be reached at this energy – and decreases at SPS energies to $\approx 16.5\%$. Such a decrease of the scaled kaon yield from AGS to SPS energies is hard to obtain in a hadronic transport model. On the contrary, the higher temperatures and particle densities at SPS energies allways tend to enhance the K^+/π^+ yield closer to its thermal equilibrium value of $\approx 20 - 25\%$ [31] at chemical freezeout and temperatures of $T \approx 150$ MeV. Thus the steep rise of the strangeness yield and its decrease indicates the presence of nonhadronic degrees of freedom which might become important already at about 4 A-GeV; according to our present understanding such nonhadronic degrees of freedom should be attributed to partons, i.e. quarks and gluons.

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